X-660-73-237

PREPRINT

NASA TM X-70448

CONSISTENCY OF COSMIC-RAY SOURCE ABUNDANCES WITH EXPLOSIVE NUCLEOSYNTHESIS

B. KOZLOVSKY

R. RAMATY

AUGUST 1973

GSFC — GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

(NASA-TM-X-70448) CONSISTENCY OF COSMIC-RAY SOURCE ABUDANCES WITH EXPLOSIVE NUCLEOSYNTHESIS (NASA) 14 p HC $3.00 CSCL 03B

N73-30768

Unclas

G3/29 11978

Consistency of Cosmic-Ray Source Abundances with Explosive Nucleosynthesis

B. Kozlovsky*
R. Ramaty

Laboratory for High Energy Astrophysics
Goddard Space Flight Center
Greenbelt, Maryland, USA

* NAS/NRC Senior Resident Research Associate on leave from Tel-Aviv University.

Several studies (1,2) exist in the literature which compare abundances of elements in the cosmic-ray sources (CRS) with solar system (SS) abundances. Their results, however, are in general inconclusive, because the uncertainties in the elemental abundances in both the CRS and the SS preclude the deduction of any systematic trend in the ratios of these two sets of abundances (CRS/SS). But, by limiting the comparison to elements for which the uncertainties are small (C, O, Mg, Si, Fe), we find that the values of CRS/SS are about 1 for Mg, Si, and Fe, and are significantly less than 1 for C and O. This result could be explained if all CRS abundances were the same as those obtained from explosive nucleosynthesis (3,4,5), and if the solar system were enriched in C and O. Such a model is consistent with the fact that in the SS abundances Mg, Si, and Fe are believed to be produced by explosive nucleosynthesis, while C and O are mainly products of other processes (6). We now proceed to examine the details and implications of this suggestion.

The abundance of cosmic rays at their sources can be calculated from their observed abundance at the top of the atmosphere using models for cosmic-ray propagation from the sources to earth and nuclear fragmentation reactions during propagation. The results of these calculations are relatively insensitive to the exact propagation model used (7); however, in order to obtain precise cosmic-ray source abundances, it is essential to have more reliable fragmentation cross sections (8).

The first two columns in Table 1 show the observed abundance of cosmic rays near earth normalized to iron at about 1 GeV/nucleon. Recently, measurements at higher energies have become available and they indicate some departures from these ratios. Most of the variations, however, could result from energy dependent cosmic-ray propagation, with the possible exception of iron which we shall discuss below.

As can be seen from Table 1, the two sets of measured abundances are consistent, except for Cr, O, and C. As we shall see below, the discrepancies in the C/Fe and O/Fe ratios do not affect our conclusions. The discrepancy in the Cr abundance is sufficiently large to preclude the use of this nucleus in testing our proposed model.

The third column in Table 1 represents the contribution of secondary nuclei to the observed cosmic-ray abundances. We define secondary nuclei as particles which are produced by spallation reactions of cosmic rays with matter between the sources and earth. The secondary contributions in Table 1 were calculated in ref. 7 for an exponential distribution of path length using the observed abundances of ref. 9 and nuclear cross sections which are essentially the same as given in ref. 8. By comparing the first and third columns of Table 1 (strictly speaking we cannot directly compare the second and third columns), we can divide the elements of Table 1 into 3 groups. These are shown in Table 2.

The first group is definitely present in the cosmic-ray sources, and the errors involved in the source abundances can be considered as small. This is the group upon which we essentially base our model. The last group in Table 2 consists of elements which, in the cosmic rays, are almost entirely of secondary origin; no test of our model can be made for nuclei in this group. Elements in the second group in Table 2 are probably also present in the cosmic ray sources, but the source abundances are uncertain because of the large secondary contributions. The test for our model, however, should finally come from nuclei in this group.

Table 3 shows the ratios CRS/SS for the elements in group 1 of Table 2 and Ne. These ratios were obtained by solar system abundances from reference 6 (also shown in Table 1)

Let us now discuss these ratios. The abundances of Fe, Si, and Mg in the solar system are taken from meteorites, but they are consistent with photospheric abundances as well (6). In fact, these elements are part of a set of elements used by Cameron to normalize the meteoritic and photospheric abundances. We consider, therefore, that the error in the solar system abundances of Fe, Si, and Mg is small. In the cosmic rays, the error in the measured abundances of Fe, Si, and Mg is about 20% or less. Since for these nuclei the secondary contributions are less than about 20%, even if there is a factor of 2 uncertainty in the fragmentation cross-sections, this will only contribute a 10% error. We thus estimate that the total error in the cosmic-ray source abundances for Fe, Si, and Mg is about 25%.
When this error is taken into account, the ratios CRS/SS for these nuclei are consistent with 1. Since Mg, Si, and Fe are believed to be the products of explosive nucleosynthesis (3, 4, 5), we suggest as a possible rule that the ratio CRS/SS will always be close to 1 for elements which in the solar system are produced by explosive nucleosynthesis.

The abundance of O and C in the solar system are taken from photospheric measurements (6). Inspection of these abundances as obtained by various techniques and phospheric models (11) reveals differences of not more than 50% of the values in Table 1. In the cosmic rays, there could be an uncertainty of 25% in the abundances of O and C relative to iron and an additional 10% uncertainty from secondary contributions. Thus, the total uncertainty in the CRS/SS ratios for O and C is certainly less than a factor of 2, and hence these ratios are definitely less than 1. We interpret this result as an indication that either in the solar system or in the cosmic rays, carbon and oxygen have a different origin than Mg, Si, and Fe. Because it is believed that in the solar system a major part of the carbon and oxygen are not produced by explosive nucleosynthesis (6), the departure of the CRS/SS ratios for C and O from 1 are probably the result of the enrichment of the solar system abundances of these elements from other processes of nucleosynthesis (such as hydrostatic helium burning (12)).

Furthermore, we suggest that all cosmic-ray source abundances from C to Fe should be the same as those obtained in explosive nucleosynthesis. The first test of this suggestion is the C/O ratio. In the cosmic-ray sources this ratio is about 1 (see Table 1), a value close to that obtained in explosive nucleosynthesis for a fairly wide range of initial conditions (3). In the solar system, the C/O ratio is about 0.5 (Table 1), and it is produced by the various contribution of different nucleosynthesis processes to the abundances of these elements. It should be noted that in the solar cosmic rays, the C/O ratio is also close to 0.5 over a range of energies (13). Therefore, the different C/O ratio in galactic cosmic rays probably cannot be attributed to an acceleration mechanism.

Let us now examine our suggestions for the second group of nuclei in Table 2. For some of these nuclei the nominal values of CRS/SS is consistent with our rules. Thus, for Ca, Al, and Na, CRS/SS is sufficiently close to 1, as expected since these nuclei in the solar system are believed to be produced by explosive nucleosynthesis. Since N in the solar system is not produced mainly by explosive nucleosynthesis, CRS/SS is significantly less than 1 for this element.

The CRS/SS ratio for Mn is uncertain, mainly due to uncertainties in the Mn abundance in the cosmic-ray sources. These uncertainties come both from difficulties in separating Mn from Fe in the cosmic rays, and from uncertainties in the fragmentation cross section of Fe into Mn.

For S, the uncertainty in the CRS/SS ratio comes from both the cosmic rays and the solar system. The contribution of secondaries to the observed sulfur abundance is about 50%; an uncertainty of a factor of 2 in fragmentation cross sections could introduce a 50% increase in the CRS abundance. In addition, there is a large uncertainty in the solar system abundances of sulfur. The S abundance in meteorites of different types varies from 0.14 to 0.6 (6). Cameron preferred the value of 0.6 because he could produce it, theoretically, by quasi-statistical equilibrium. Because of the difficulties involved in such a theoretical determination, we still regard the abundance of sulfur as uncertain in the above range. It should be noted that solar cosmic-ray observations (14) could be consistent with a lower sulfur abundance.

For Cr, the uncertainty in the CRS/SS ratio comes mainly from the cosmic-ray observations. For Ar, the solar system value (6) is based entirely on theoretical quasi-equilibrium calculation. According to our model, the reconciliation of the CRS/SS ratio of Ar with 1 will require a lowering of the solar system value or of the decrease of the contributions of secondaries to the observed cosmic-ray argon abundance.

Consider now the ratio CRS/SS for neon. From Table 1, this ratio is significantly less than 1 indicating that Ne in the solar system is not produced by explosive nucleosynthesis. An examination of the uncertainties in both the cosmic rays and the solar system abundances indicates that it is difficult to raise CRS/SS for neon by more than 50%. It should be noted, however, that the solar system abundance of Ne comes only from solar cosmic-ray observations (13). As to the solar system origin of neon, Arnett (3) suggests that Ne^{20} (which constitutes ~90% of all neon) is produced by explosive carbon burning and this would present a conflict in our model. But Vidal et al. (15) have shown that Ne^{20} could be produced by nonexplosive helium burning. We suggest that the origin of Ne^{20} in the solar system should be further investigated. It should also be noted that no Ne^{22} was found in the cosmic-ray observations of Webber et al. (16). This would be consistent with the fact that Ne^{22} is not produced by explosive nucleosynthesis (3).

Let us examine some of the consequences of our model. We first consider the C/Mg ratio in the cosmic-ray sources, because in explosive nucleosynthesis both C and Mg are produced from carbon burning only (3). According to Arnett (3), by varying the temperature from 1.0×10^9 °K to 2×10^9 °K, C/Mg varies from about 30 to less than 2 (at the same time C/O varied by only a factor of 2). This should be compared with the C/Mg ratio in the cosmic-ray sources which is between 4 and 5. We suggest, therefore, that the C/Mg ratio can be a very important and sensitive tool for the determination of the initial conditions of the explosive nucleosynthesis.

Another interesting feature of our model are the abundances of the odd nuclei, Al and Na. According to Arnett and Clayton (5), these abundances depend of a quantity $\eta = (N_n - N_p)/(N_n + N_p)$, where N_n and N_p are the total number of bound and free neutrons and protons in the region of nucleosynthesis. This quantity is thought to increase over the lifetime of the galaxy; at later times there are more neutron-rich isotopes present in galactic material than at earlier times. The abundances of Na and Al increase with increasing η. The fact that the abundance of these odd nuclei appear to be the same in the cosmic rays as in the solar system (Table 1), may indicate that η did not change appreciably since the formation of the solar system (the age of the cosmic rays is neglible in comparison with the age of the sun).

From cosmic-ray observations (17) at energies greater than a few GeV/nucleon it has been found that the Fe/(C+O) ratio increases with increasing energy. Ramaty et al. (18) have suggested that this increase may be due to an additional source of Fe at high energies. Even though there may be other explanations for this effect, the possibility of a second source of almost pure iron (such as the surface of a neutron star) might explain why the Si/Fe and Mg/Fe ratios are somewhat less than 1.

We should finally mention that other comparisons, similar to ours, were recently made. Casse and Goret (19) suggest that there is a correlation between CRS/SS and the first ionization potential of the elements. We feel that because of the uncertainties that we have discussed, this model is rather inconclusive at the present time. Cowsik and Wilson (20), on the other hand, have arrived at essentially the same conclusions regarding the ratios CRS/SS as we did, except that they do not associate their results to explosive nucleosynthesis.

In summary, we have presented a model in which the cosmic-ray abundances from C to Fe are consistent with explosive nucleosynthesis. One of the main virtues of this model is that it explains the carbon-to-oxygen ratio in the cosmic rays. The principal test of the model will come from a better determination of the abundances of elements in group 2 of Table 2, both in the cosmic rays and the solar system.

TABLE 1

Element	Cosmic Ray Abundances at Earth			Cosmic Ray Source Abundances		Solar System Abundances
	Observed		Secondary Contribution			
	Ref. 9	Ref. 1	Ref. 7	Ref. 7	Ref. 1	Ref. 6
Fe	1 ± .12	1	0	1	1	1
Mn	.08 ± .03	0.08	.033	.045	0.025	0.01
Cr	.31 ± .09	0.1	.10	.20	<0.03	0.015
V	.09 ± .03	0.05	.096	-.006	<0.01	3×10^{-4}
Ti	.18 ± .05	0.13	.18	-.007	0.035	3×10^{-3}
Sc	.027 ± .02	0.04	.064	-.033	0.015	4×10^{-5}
Ca	.18 ± .05	0.25	.18	-.003	0.13	0.087
K	.053 ± .027	0.11	.14	-.070	0.019	5×10^{-3}
Ar	.18 ± .05	0.12	.14	.032	0.015	0.14
Cl	.044 ± .026	0.05	.068	-.019	<0.01	6.9×10^{-3}
S	.31 ± .09	0.33	.15	.13	0.175	0.6 - 0.14
P	.053 ± .12 .044	0.04	.05	.0022	<0.01	0.01
Si	1.33 ± .18	1.29	.16	.89	0.89	1.2
Al	.18 ± .09	0.25	.11	.051	0.11	0.1
Mg	1.86 ± .18	1.96	.30	1.11	1.2	1.28
Na	.27 ± .14	0.28	.21	.040	0.067	0.072
Ne	1.8 ± .2	1.7	.49	.85	0.868	4.14
F	.18 ± .1	0.13	.27	-.059	<0.025	3×10^{-3}
O	7.6 ± .35	9.5	.61	4.27	5.47	25.9
N	2.4 ± .18	2.6	1.34	.62	0.565	4.5
C	8.8	10.8	1.15	4.23	5.15	14.2

TABLE 2

Group	Approximate Percentage of Secondary Origin
1) Fe, Si, Mg, O, C	<20%
2) Mn, Cr, Ca, Ar, S, Al, Na, Ne, N	>20% and <100%
3) V, Ti, Sc, K, Cl, P, F, B, Be, Li	~100%

TABLE 3

Element	C	O	Ne	Mg	Si	Fe
CRS/SS	0.33	0.19	0.21	0.9	0.74	1

References

1) Webber, W. R., Damle, S. V. and Kish, J. Astrophys. Space Sci. 15, 245 (1972)
2) Shapiro M. M., Silberberg R. and Tsao, C.H. Space Research, 12, 1609, (1972)
3) Arnett, W. D. Astrophys. J. 157, 1369 (1969)
4) Truran, J. W. and Arnett, W. D. Astrophys. J. 160, 181 (1970)
5) Arnett, W. D. and Clayton, D. D. Nature, 227, 780 (1970)
6) Cameron A. G. W., Preprint (1973)
7) Ramaty, R. and Lingenfelter, R. E. in Isotopic Composition of the Primary Cosmic Radiation (edit. Dauber, P.M.) (Danish Space Research Institute, Lyngby, 1971)
8) Silberberg, R. and Tsao, C. H., Astrophys. J. Suppl. 25, 315 (1973)
9) Shapiro, M. M. and Silberberg, R. Annu. Rev. Nucl. Sci. 20, 323 (1970)
10) Juliusson, E., Meyer, P. and Müller, D., Conference Papers, 13th International Conference on Cosmic Rays, Denver, Colorado, paper 247 (1973)
11) Müller, E. A. in Origin and Distribution of Elements (edit. Ahrens, L.) (Pergamon Press, 1968)
12) Clayton, D. C. Principles of Stellar evolution and Nucleosynthesis (McGraw-Hill, 1968)
13) Teegarden, B. J., von Rosenvinge, T. T. and McDonald F. B. Astrophys. J. 180 1571 (1973)
14) Bertsch, D. L., Fichtel, C. E. and Reames, D. V. Astrophys. J. 171, 169 (1972)
15) Vidal, N. W. Shaviv, G. and B. Kozlovsky, Astron. and Astrophys., 13 147 (1971)
16) Webber, W. R., Lezniak, J. A. and Kish J. Astrophys. J. (Letters) 183. L81 (1973)

17) Ormes J. F. and Balasubrahmanyan, V. K., Nature 241, 95 (1973)

18) Ramaty, R., Balasubrahmanyan, V. K., and Ormes J. F., Science, 180, 731 (1973)

19) Casse, M. and Goret, P. Conference Papers, 13th International Conference on Cosmic Rays, Denver, Colorado, paper 359 (1973)

20) Cowsik, R. and Wilson, L. W., Conference Papers, 13th International Conference--Cosmic Rays, Denver, Colorado, paper 359 (1973)